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GAMMA RAY REFLECTION

Richard Anton Mergl

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GAMMA RAY REFLECTION

by

Richard Anton Mergl

A Thesis Submitted to the
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The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Engineering

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I. INTRODUCTION

At the close of the year 1956, reactor technology in the free world had progressed to the point where there were several experimental reactors in operation, one stationary reactor power plant designed and used for the production of power (Calder Hall), and a mobile reactor installation in the submarine USS Nautilus which had demonstrated its effectiveness as a power plant by propelling the Nautilus for two years without refueling. Despite the successes which have been attained, many problems remain to be solved, and in an engineering field as young as that of nuclear engineering, there is considerable room for improved techniques.

Theoretically, there are several different radiations which might escape from a reactor including alpha and beta particles, protons, fission fragments, neutrons, and gamma rays or x-rays. Since neutrons and gamma rays or x-rays are by far the most penetrating forms of radiation, preliminary considerations in the design of a reactor shield are often limited to the attenuation of these radiations to the desired level.

In the design of shields for stationary reactors, the primary considerations are usually those of economy and availability of materials consistent with providing suitable radiation protection for operating personnel. In spite of improved designs leading to greater efficiency, reactor shields have

become larger and more expensive in recent years. As a result, they require greater space in buildings which are in themselves more expensive, and they are inconvenient for auxiliary apparatus must be made to extend farther between radiated and shielded locations.

In the design of mobile reactor shields, the controlling design criteria are those of weight and size which must be kept to a minimum. These criteria are perhaps most important in the aircraft industry and to achieve this end consideration is occasionally given to costly and rather uncommon materials. As a result, there is a great deal of incentive to develop the best possible shield designs with perhaps the most pressing requirements being those associated with mobile reactors.

One shield design which has been proposed was based on the principle of gamma ray reflection utilizing many curved elements to deflect the gamma radiation rather than absorb it. The purpose of this investigation was to examine several different materials to determine whether gamma ray reflection does occur in them to such an extent that large scale deflections can be observed.

II. REVIEW OF LITERATURE

A great deal of information has been published on the subject of x-ray reflection with some scattered information relative to the applications of this principle. On the other hand, very little published information is available concerning reflection of gamma rays despite the fact that the principle of reflection of gamma rays was utilized in 1914 by Rutherford and Andrade (1) in the determination of the wavelengths of gamma rays. Accordingly, a review of the literature with the intent of briefly outlining the characteristics of x-rays and gamma radiation with some insight as to the present and possible future applications of the reflective nature of the radiation was considered in order.

Both gamma-rays and x-rays have been shown by experimentation to be electromagnetic radiations with identical properties making it difficult to differentiate between the two on the basis of their properties. The terms gamma-ray and x-ray are used primarily to distinguish between the sources of the rays; gamma-rays being electromagnetic radiations which originate in the nucleus as in the decay of a nucleus at an excited level to its ground state, while x-rays are high-energy electromagnetic radiations which result from jumps of extranuclear electrons in atoms or which are produced by artificial sources such as a Coolidge tube or a betatron.

In 1895 Wilhelm Conrad Roentgen (2a) discovered x-rays when he found that the operation of a cathode ray tube produced fluorescence in a platinum-barium-cyanide screen placed some distance from the tube. He traced the source of rays which caused the fluorescence to the walls of the cathode ray tube and in his first communications he reported that x-rays were produced when the cathode rays struck any solid object. By interposing various thicknesses of many substances between the tube and the screen he found that intensity of fluorescence was reduced but not completely obliterated and concluded as a result of his experimentation that all substances were more or less transparent to x-rays. He also found that x-rays could expose a photographic plate, and discharge negatively or positively charged bodies, but were not deflected by a magnetic field. Roetgen tried unsuccessfully to confirm phenomena of refraction, diffraction, and reflection of x-rays but in 1899 Haga and Wind (2b) succeeded in obtaining a diffraction pattern and in 1923 Compton (3a) first observed the phenomena of total reflection. In the report of his work, Compton noted that although previous attempts to measure index of refraction of different substances of x-rays had failed, deviations from Bragg's equation (which gives the condition for reflection of x-rays from a series of atomic planes) had been observed initially by Stenström (3b) using wavelengths greater than 2.5 Angstroms. Other physicists had also

noticed that the wavelengths calculated from measurements in the different orders of reflection did not exactly agree with each other and Stenström concluded that the experimental evidence indicated appreciable refraction of the x-rays. Compton reasoned that for the case of ordinary x-rays traversing matter composed of light atoms, the frequency of the radiation is considerably higher than the natural frequency of the electrons and thus the Drude-Lorentz equation for the index of refraction of a medium for radiation of very high frequency could be simplified to

$$\delta = 1 - \mu = \frac{ne^2}{2\pi m \nu^2} \qquad (1)$$

where μ is the index of refraction, n represents the number of electrons per unit volume of the medium, e and m represent the charge and mass of the electron, respectively, and ν is the frequency of the radiation. Applying this equation to x-rays of 1.473 Angstroms traversing calcite, Compton obtained a value for the index of refraction which was less than unity by about 8 x 10^{-6}. He observed that this value agreed closely with experimental results obtained by Duane and Patterson (3c) using the same wavelength and medium. He concluded, therefore, that the consistent changes in apparent wavelength with order which had been observed were due to refraction. Since the index of refraction for x-rays is less than unity, a beam of x-rays

striking a plane surface at a suitable angle should be totally reflected, the critical glancing angle being given by

$$\sin \theta = \sqrt{2\delta} \qquad (2)$$

or since the angles involved are small, this may be simplified to

$$\theta = \sqrt{2\delta} \qquad (3)$$

Compton set up experimental apparatus in which x-rays were incident at small angles on a flat plate glass mirror with an ionization chamber positioned to determine intensity of the x-rays at a value of $\phi = 2\theta$. With the plate glass mirror as a reflecting surface, he noted that x-rays were of maximum intensity when the angle ϕ was equal to 2θ indicating an approximate specular reflection of the x-rays at these small angles. No appreciable reflection was observed at angles as large as $\phi = 18$ minutes which meant that for the greater part of the x-ray beam, the critical glancing angle θ was less than 9 minutes. In order to determine whether the observed phenomenon was really one of total reflection, Compton measured the total energy in each of the primary and reflected beams and found that the ratio of reflected beam energy to that of primary beam was of the order of 0.91 indicating that the greater part of the beam had been reflected. Reflection of tungsten L line (1.279 Angstroms) from a silvered glass mirror coated with a thin film of lacquer indicated that the

critical glancing angle for glass was 10 minutes, for lacquer 11 minutes, and for silver about 22.5 minutes. In 1927, R. L. Doan (4) published results of similar experimentation carried on by him with Compton's advice, which he had undertaken to measure indices of refraction of various substances by the method of total reflection. Most of the surfaces used by Doan for reflection were prepared by sputtering various metals on optical glass surfaces, thus obtaining uniform surfaces of considerable brilliance. Under the conditions of the experiment, a reflected beam was obtained which was in most cases just as sharply defined as the primary beam indicating again a specular type reflection rather than a diffuse reflection. Some of the data which Doan obtained are tabulated in Table 1 and plotted in Figure 1. The resultant curves have been extrapolated to a value of wavelength of 0.01 Angstroms which is of the order of the gamma ray wavelengths observed from Co-60. In the plotting of the data, the general shapes of the curves were plotted to conform to the shape of the curve indicated by nickel for which Doan had presented the most complete data. A straight line extrapolation was employed, to obtain what was considered the least optimistic values of critical angles at typical gamma wavelengths, in view of the general trend indicated at higher wavelengths, It is entirely possible, however, for the curves to follow a downward trend below 0.7079 Angstroms but in view of the work by DuMond (5) one would not expect this result. Gamma ray wavelengths have

Table 1. Critical angles for reflection of x-rays[a]

X-ray wavelength (Angstrom units)	Reflecting surface	Critical angle θ_c
1.537	Glass	13' 36"
0.7078		6' 18"
1.537	Copper	20' 34"
1.389		19' 36"
1.537	Silver	26' 42"
0.7078		11' 42"
1.537	Nickel	24' 40"
1.389		16' 09"
0.7078		10' 15"
1.537	Speculum	23' 08"
0.7078		10' 52"
1.537	Gold	31' 24"
0.7078	Steel	9' 35"

[a] Data from Doan (4).

been measured with the Bragg spectrometer as small as 0.016 Angstroms but at these and smaller wavelengths very small angles involved limit accuracy of the Bragg type of single crystal spectrometer. DuMond and his co-workers have measured wavelengths smaller than 0.01 Angstrom with an accuracy of 10^{-5} Angstroms with a curved crystal spectrometer wherein gamma rays from a source are reflected from crystal planes of a curved quartz crystal into a detector. A reflected angle can

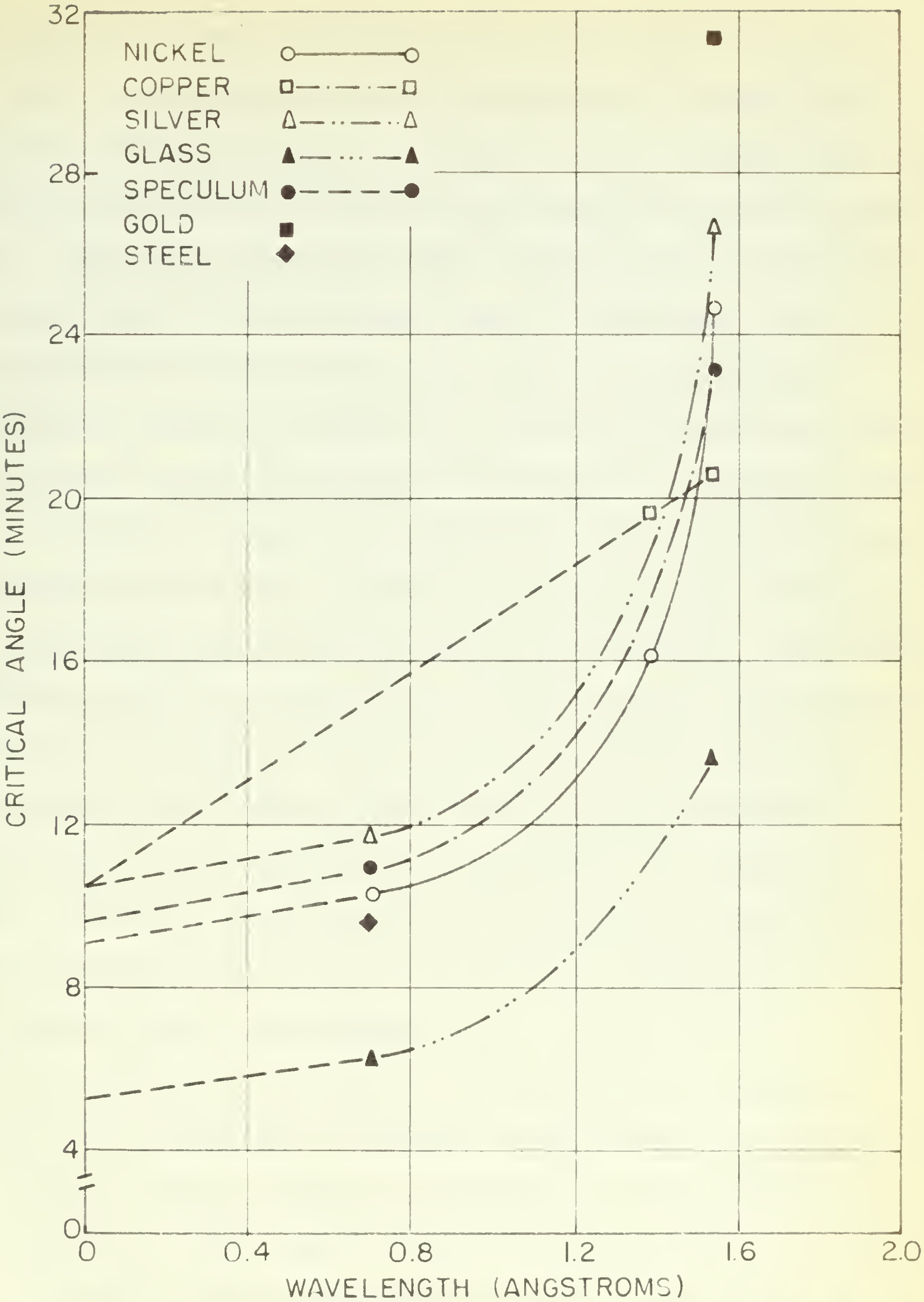


Figure 1. Critical angle *versus* wavelength for reflection of x-rays.

be measured and the wavelength of the gamma ray determined.

Some justification for the extension of the data for the critical reflection angles of x-rays to that of gamma rays may be found in the identity of the characteristics of the radiations. Both gamma rays and x-rays travel with the velocity of light, can be diffracted and made to interfere, eject photoelectrons from materials, and resist being bent by electric and magnetic fields. The wavelengths of both types of radiation can be measured by the method of glancing angle reflection from a crystal as mentioned above and herein lies one application of the reflective nature of x-rays and gamma ray radiation, that of measuring the wavelengths. Historically, gamma rays were considered more penetrating than x-rays but modern technology has produced accelerators which can produce x-rays of the order of 100 Mev. which is considerably greater than gamma ray energies associated with radioactive decay. To sum up the comparison, it can be said that despite the fact that x-rays and gamma rays have a different origin, they have the same characteristics.

The reflective property of x-rays has been used by Parratt (6) to determine structural irregularities of a surface by causing a beam of x-rays to impinge upon the surface to be investigated at less than the critical angle for total reflection and analysing the peculiarities in the reflected intensity of the beam.

Although the reflective nature of gamma rays has been

known for many years and has been applied to the measurement of gamma ray wavelengths by DuMond and others, there is a relative scarcity of published information on the subject of gamma ray reflection and possible applications doubtless due to the very small critical angles which are involved. Proell (7) published a paper in which he proposed making use of the reflective nature of gamma rays to construct a gamma ray shield which he hypothesized would result in a thinner and lighter shield than presently utilized. A reduction in the size and weight of required shielding would be particularly applicable to mobile reactors such as are being designed for aircraft and also to nuclear powered manned space vehicles when modern technology has made space travel possible. The feasibility of reflective type shielding relies first of all on the identity of the characteristics of gamma rays and x-rays, a valid premise on the basis of present day knowledge. With this initial postulate, Proell assumed that gamma rays can be totally reflected as had been demonstrated with x-rays and that the values of the critical angle for reflection would be large enough to utilize the reflective property of gamma rays. Accordingly, he proposed that the data presented by Doan (4) and others relating the critical angle for reflection to the wavelength of x-ray radiation could be extrapolated to gamma ray wavelengths to yield valid approximations of the critical angle for reflection as indicated in Figure 1. Proell then suggested that a shield could be constructed of several planar

elements with arcs of 90° stacked closely together to make a bank of elements which would theoretically deflect the gamma rays 90° from the original direction. In order to prevent the escape of those gamma rays which did not intercept the bank at the critical angle or less, he proposed that a second bank of elements be positioned behind the first such as to deflect the gamma rays in a direction opposite to the first. In Figure 2 a schematic diagram of the shield arrangement for a mobile vehicle has been adapted from Proell's paper to illustrate his proposed shield design. The reflective shield is interposed between the reactor and the crews compartment in such a way that the gamma radiation included between rays A and D are deflected up to 90°. Gamma radiation emitted outside of this sector was considered to be of little consequence although one would expect that some gamma rays could be scattered inboard once past the shield and thus be a threat to the safety of the crew. The rays have been depicted from a single point only for purposes of illustration. Considering the gamma ray C, given enough planar elements in the bank, it is very likely to intercept a planar element at less than the critical angle and thus reflect several times from this element until it emerges from the shield. Next consider the ray B which cannot intercept a planar element in the first bank at the critical angle or less unless perhaps it is scattered and its direction changed so that when it next encounters an element it is incident at the

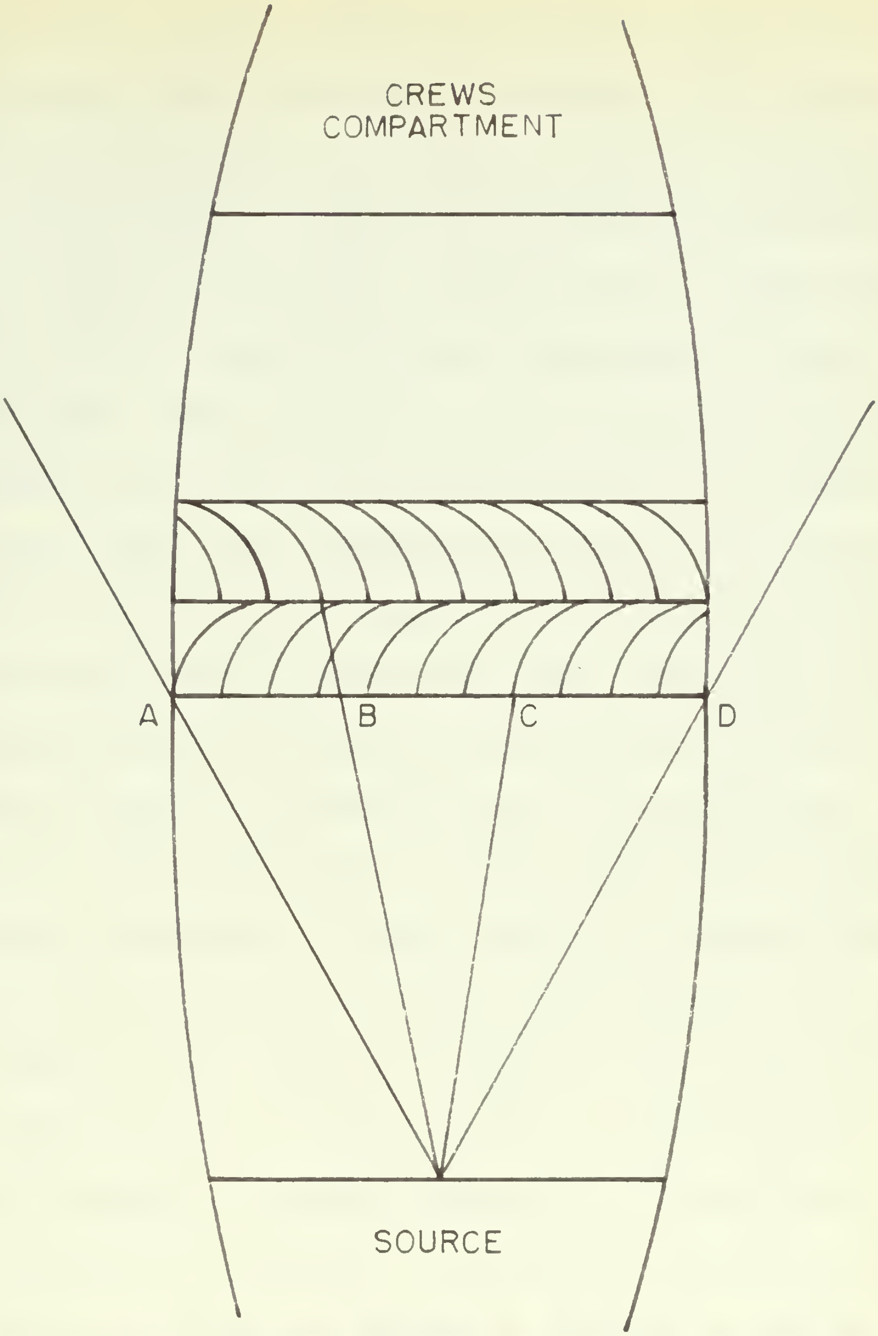


Figure 2. Schematic diagram of the shield arrangement for a mobile vehicle. [Adapted from Proell (7)]

critical angle or less. Proell postulated that such a ray would penetrate the first bank of elements and would then be in a favorable position to intercept a planar element in the second bank and after a series of reflections be reflected out of the bank to the left. On the basis of this simplified approach, Proell's proposal seems reasonable, however, he has only considered that the gamma rays will either reflect or pass through the first bank transparent-wise and has not considered that rays which intercept the first bank at an angle unfavorable for reflection might be scattered so that they enter the second bank unfavorably also. Some gamma rays then can scatter through the shield negating Proell's postulate that the two banks of elements would be impermeable. If, however, the basic principle of reflection can be proved valid and a bank of elements of small radius of curvature developed which would be effective, Proell's idea could be extended to include several more banks in addition to the two proposed which would increase the possibility of all the gamma rays eventually striking a planar element at a favorable angle and reflecting out of the shield. Whether the resultant configuration would be a saving of weight or space or both depends upon the materials used for the banks of elements and the radius of curvature of the elements.

A serious limitation imposed upon the design of such a shield results from a consideration of the spacing of the

elements which is dependent upon the radius of curvature of the elements and the critical angle for total reflection. Proell postulated that the condition for impermeability of the shield should be that any gamma ray which strikes the shield normally should be reflected. Figure 3 is a schematic representation of two elements AB and CD of the first bank. In accordance with the theory, this bank of elements should cause all gamma rays which are normal, such as the one depicted, as well as all gamma rays which strike the bank from the left to enter the reflection cycle and be reflected from the shield. Since the normal ray shown represents the least favorable condition, the bank of elements must be designed in such a manner that this normal ray will strike an element at the critical angle θ. An equation relating the radius of curvature to the spacing between elements for a given critical angle may be developed from simple geometry as follows:

$$\cos \theta = \frac{r - x}{r} \qquad (4)$$

so that

$$x = r\,(1 - \cos \theta) \qquad (5)$$

where

x = spacing between the elements

r = radius of curvature of the elements

θ = critical angle for reflection.

If the critical angle is of the order of 9' and it is desired to limit the thickness of a single bank to 5 cm., the radius is

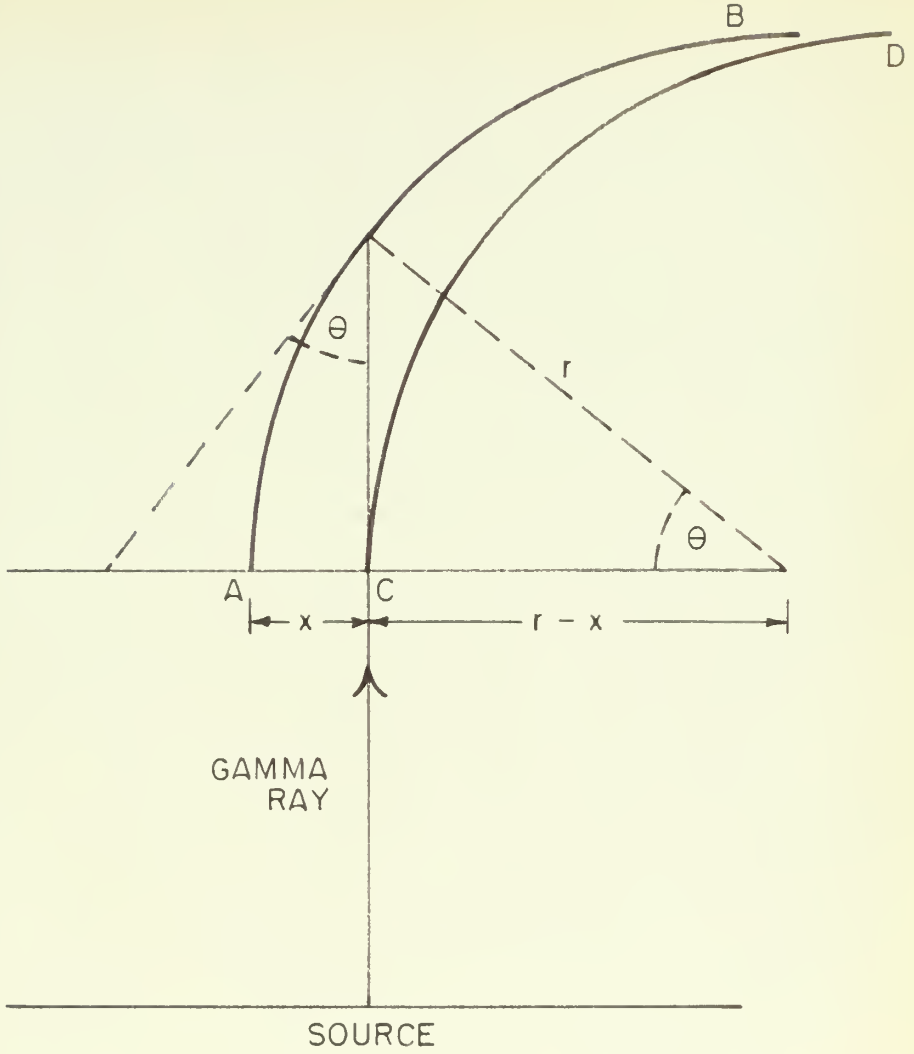


Figure 3. Schematic representation of two elements AB and CD of the first bank of elements.

then fixed at 5 cm. and the value for the maximum spacing allowable between elements becomes:

$$x = r\ (1 - \cos \theta)$$

$$x = 5\ (1 - 0.999996)$$

$$x = 2000 \text{ Angstroms.}$$

In order to arrive at an efficient design for the shield, it would be desirable to have the individual elements as thin as possible and certainly no thicker than the spacing between them. The construction of a bank of elements each with a thickness less than 2000 Angstroms and separated uniformly by the same amount or less is a difficult task. Since the spacing and the radius of curvature are directly related, the possibility exists of increasing the radius of curvature until the value of element thickness is such that the elements can be constructed with present commercial techniques. For example, aluminum foil is rolled commercially to gages as thin as 0.00025 cm. Assuming that the choice was made for the elements to be fabricated from such foil and that the spacing between the elements was to be of the same order of magnitude, one arrives at a value for the radius of curvature of 62.5 cm. using the relation previously developed. This would result in a shield thickness of approximately four feet if one were to use only two banks of elements and might be tolerable spacewise if the resultant shield were light. However, the problem of arranging the thin foils with the proper spacing still remains.

Commercial sheet material is available in thicknesses of 0.0799 mm. and substituting this value into the equation above for the element spacing results in a required radius of curvature of approximately 200,000 cm., an extremely impractical result to say the least.

One approach to the solution of the problem would be to study various materials to attempt to find larger critical reflection angles for gamma rays. On the basis of presently available information, one is not likely to arrive at a solution with this approach for even if a value for the critical angle as large as 5° could be attained, with the use of the thinnest commercial sheet available, a radius of curvature of approximately 210 cm. would still be required. Another approach would be to utilize the spacing present in a crystal lattice and consider the design of a shield of bent crystal layers. Since the order of magnitude of spacing of crystal planes may be taken as 5 Angstroms, a radius of curvature of 0.12 mm. would be theoretically possible considering a value of the critical angle for reflection of 9 minutes.

In addition to these suggestions, Proell proposed that a solution to the problem might be approach by studying simple plane elements to determine accurately the critical angle for reflection for gamma rays and also to determine whether reflection from crystal planes would be total reflection as postulated. He also suggested the study of a single curved element as applied to the problem of reflection and the study of a small

bank of curved elements for efficiency and practicality.

In 1956, Crocker (8) conducted a study of a series of small banks of curved elements to test Proell's theory of the reflective type shield. Several simplifying assumptions were made in addition to those proposed by Proell. Since aluminum foil was the only readily available and economical foil which could be obtained in the quantity desired, Crocker assumed that aluminum would exhibit essentially the same properties as the materials examined by Doan and further assumed that the critical angle for reflection was of the same order of magnitude for aluminum as for the other materials. Several banks of foil were prepared as quarter circles and arranged to constitute a single reflecting bank so that in theory the incident gamma rays would either pass through the shield or be reflected 90°. Although the requirements of element thickness, spacing, and radius of curvature could not be met with the material used, Crocker postulated that the theory had been approximated sufficiently well that some indication of reflection would be obtained. While the results obtained cannot be considered conclusive proof of the feasibility of a reflective type shield, the experimental data indicated a slight tendency of reflection of the gamma rays since deflections were obtained which could not be satisfactorily explained on the basis of known gamma ray interactions.

III. PRELIMINARY INVESTIGATION

In the initial stages of the investigation, considerable attention was given to the proposal that a single curved element be used to effect large scale deflections of gamma radiations. The success or failure of this proposal was dependent upon two main assumptions: first, that gamma rays can be totally reflected as had been demonstrated with x-rays, and secondly, that the data presented by Doan (4) relating the critical angle for reflection of x-rays *versus* their wavelength could be extrapolated to gamma ray wavelengths and result in values of the critical angle for reflection of the order of ten minutes. In order to obtain total reflection of the x-rays, Doan prepared the reflective surfaces by sputtering various metals on optical glass surfaces, obtaining relatively thick films of considerable brilliance and uniformity. These surfaces were then burnished in order to increase the reflecting power as much as possible. In 1954, Parratt (6) obtained total reflection of x-rays using surfaces prepared by evaporating a moderately thick (2000 A^o) copper film on a smooth surface of glass. In both cases the surfaces were plane so that only a single reflection was obtained. In view of the results obtained by these men, it seemed reasonable to expect that a curved surface could be prepared in a similar manner which would be capable of causing the gamma rays to undergo a series of reflections on a curved surface until they had been

deflected the desired amount. Copper and nickel were chosen as the metals to be evaporated on a curved glass surface, copper having been chosen because it was expected on the basis of the assumptions listed above that it would exhibit a critical angle of the order of ten minutes, and nickel being chosen because it was the metal for which Doan had obtained the most complete data. (See Table 1 and Figure 1) Calculations of the radius of curvature which would be required to effect the total and repeated reflection of the incident gamma radiation was then made and results were obtained which indicated that excessively large curved elements would be required in order to obtain large scale deflection of the gamma rays. Figure 4 is a schematic diagram of the incident gamma radiation and curved element MD which has not been drawn to scale because of the small values involved but which will serve to illustrate the situation. To simplify calculations, it was assumed that the critical angle for reflection was ten minutes and that the incident gamma ray beam was cylindrical with a diameter of 1/16 of an inch. The gamma ray beam is shown intercepting the curved element such that the upper portion of the beam is just tangent to the leading edge of the element while the lower portion intercepts the element within the sector representing ten minutes of arc. The condition for total reflection of gamma ray beam is that at every point of contact with the curved element, the angle of incidence should be equal to or less than the critical angle for reflection, ten minutes. From

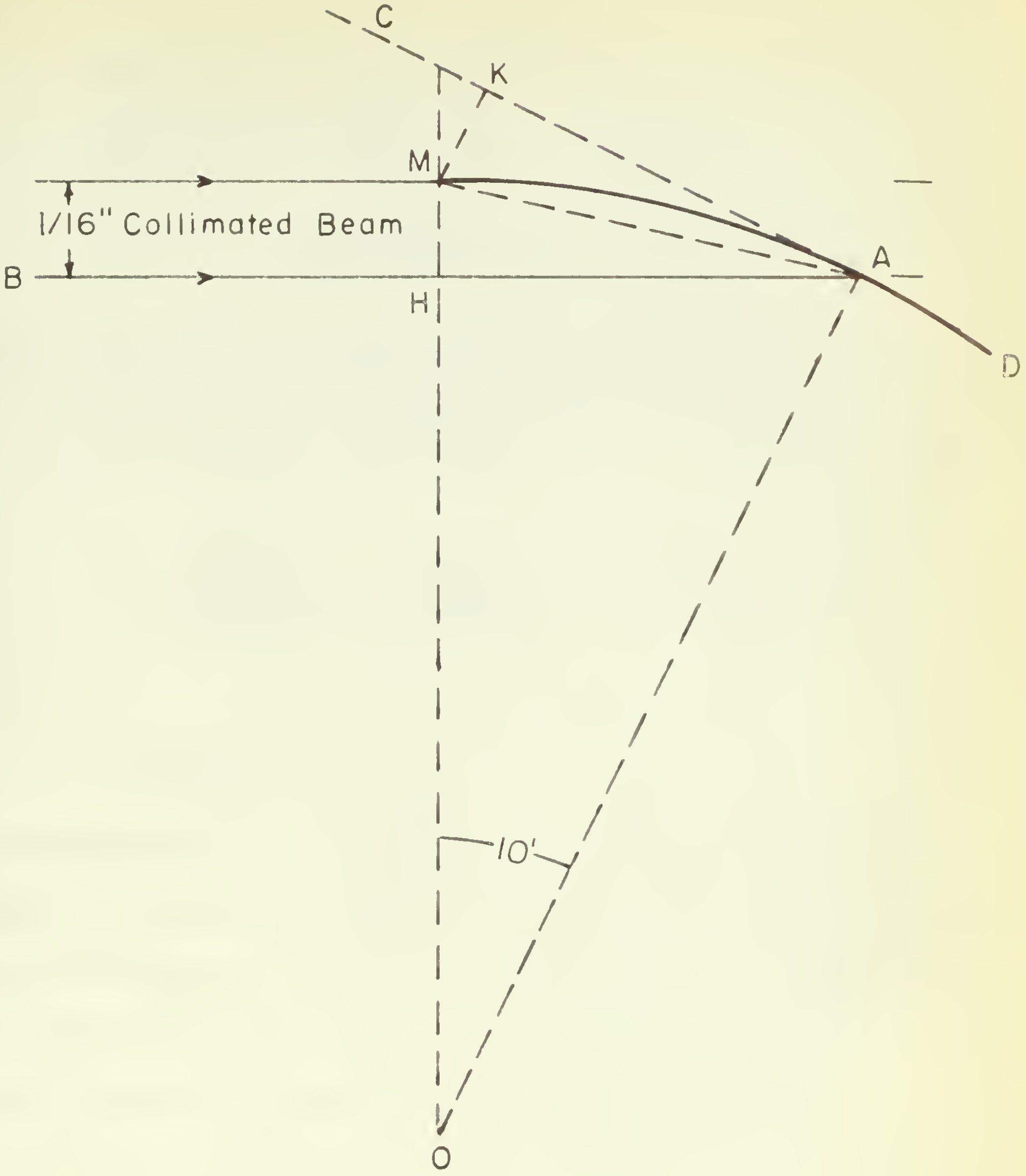


Figure 4. Schematic diagram of a collimated beam incident on a single curved element.

the geometry of the figure, the radius of curvature which is required can be calculated as follows:

angle MOA = angle CAB = 10 minutes

angle CAM = angle MAB = 5 minutes

$$\text{chord MA} = \frac{\text{MH}}{\text{sine angle MAB}} = \frac{1/16 \text{ in}}{0.00145} = 43.1''$$

Now, the length of a chord subtending an angle $\theta = 2r \sin 1/2\ \theta$ where r is the radius of curvature to be determined. Therefore,

$$r = \frac{\text{chord}}{2 \sin \frac{1}{2} \theta} \quad \frac{43.1''}{2 \sin 5'} = 14{,}900 \text{ inches}$$

or

$$r = 1242 \text{ ft.}$$

The length of an arc of a circle for an arc of θ degrees = $\frac{3.1416\ r\ \theta}{180}$ and substituting the value for r into this equation with $\theta = 45$ degrees results in a length of arc equal to 975 feet. The calculations were repeated with smaller diameter gamma ray beams but they did not result in appreciably smaller lengths of arc required to produce a large scale deflection.

It was realized that this theory could still have been tested were one to accept a lesser deflection of the incident gamma ray beam but due to the fabrication problems involved and the difficulty involved in obtaining the equipment necessary to measure very small angles of deflection, the decision was made

to abandon this method of approach since the time available for this study was limited.

Another approach to the problem of large scale gamma reflection involved the use of an electroplated material to utilize atomic spacing. The choice of materials to be used was based on the value of critical angle for reflection which was expected, the availability of the material, and the feasibility of electroplating the material selected. On the basis of the data presented in Figure 1 which indicates the critical angle for reflection versus the gamma wavelength, copper and silver were chosen since it was expected they would exhibit the largest value of critical angle. Considering then the availability of copper and silver and the relative ease with which they can be deposited electrolytically, both the copper and silver appeared to be relatively good choices.

While it was known that no semblance of a regular crystal structure would be obtained in an electrodeposited material, it was expected that gamma ray reflection would occur at interfaces and accordingly the original design called for alternate layers of copper and silver with each layer being polished before the application of a new one to create interfaces. After considering the similarity in the crystal structures of copper and silver (both form cubic lattices with not too different values of atomic radius and spacing), it was decided to simplify the process somewhat and electroplate only copper.

In addition to the possible gamma reflection from interfaces in the electrodeposited material, some reflection was also expected from twin planes which might have formed during the electrodeposition. C. S. Barrett (9a) has included an illustration of this phenomena [taken from J. B. Hess (9b)] in a discussion of stacking faults but does not indicate the conditions which are necessary to obtain such a structure.

The material to be electroplated was machined to obtain a 45° arc of a circle with a three inch radius of curvature, a height of one-half inch and a thickness of one-eighth of an inch. Four such samples were made of commercial grade electrolytic copper. The first specimen was prepared by plating 25 layers of copper with a polishing operation after the addition of each layer resulting in a build-up of one-eighth of an inch. However, instead of the smooth structure which was desired, the final product contained many grooves running along the length of the specimen indicating a non-uniform electrodeposition.

Preparation of a second specimen was then undertaken using a slower rate of deposition and a straight rather than curved base material. It was felt that this would result in smoother, more uniform layers and that the specimen could be bent to the desired curvature when completed. An analysis of the gamma reflective properties of this specimen was not included in this report but it was felt that such a specimen would be worthy of investigation.

The suggestion was made by Proell (7) that use be made of the spacing present in a crystal lattice and evaluate the possibility of designing a shield consisting of bent crystal layers. While the design of a shield for gamma radiation was beyond the scope of this report, it was decided to evaluate this proposal to the extent of determining whether bent crystal planes would be effective as reflective surfaces. Although several types of crystals were available for this study, zinc crystals proved to be the only readily obtainable crystals which were large enough to conduct the test with the apparatus proposed and which could be bent without rupturing. Once the crystals were obtained it was decided to bend them in such a manner as to utilize the most densely packed planes as curved reflecting surfaces. The crystal form of zinc is the close-packed hexagonal arrangement of which the basal plane is the most closely packed plane. The specimens used in the experimental work were approximately six inches long by one-half centimeter square with the basal planes making an angle of about 60 degrees with the length of the crystal. The orientation of the basal plane was determined by locating the cleavage plane which was taken to be the basal plane. If a sharp edge such as a knife blade is placed on the crystal parallel to the cleavage plane and tapped lightly with a hammer or similar instrument, the crystal will split quite readily leaving a very smooth, bright surface on both segments. Once the orientation

of the basal planes was determined, the crystals were bent to the desired radius of curvature and placed on the apparatus for analysis as described in a later section of this report.

IV. MATERIALS AND APPARATUS

The apparatus used in this analysis and the experimental arrangement are shown in Figure 5 with some of the shielding blocks removed from about the source container. Figure 6 is a view of the sextant and the platform upon which the specimens were mounted with four zinc crystals aligned as they were used in the final experimental run. Also shown in this figure are the other specimens described in the report. A detailed description of the apparatus follows.

A. Source and Source Container

Originally, the apparatus was designed about a Co-60 source with a strength of 100 micro-curies but early calculations indicated that this source would yield only about two counts per minute at the detector with the degree of collimation desired and estimating the efficiency of the detector at two per cent. A larger source was then obtained, a Co-60 source with a strength of 2.5 mc. which on the basis of calculations was to yield 118 cpm. under the same conditions as before. Since this was the largest readily available source which could be obtained, the decision was made to accept this low counting rate and increase the length of the count to keep the statistical errors to a reasonable value. The radioactive material was enclosed in an aluminum wafer one-eighth inch thick, with a

Figure 5. Experimental apparatus.

A. Source holder
B. Collimators
C. Platform unit
D. Shielding bricks
E. Sextant
F. Plumb
G. Polar grid
H. Scintillation detector and platform
J. Scalar

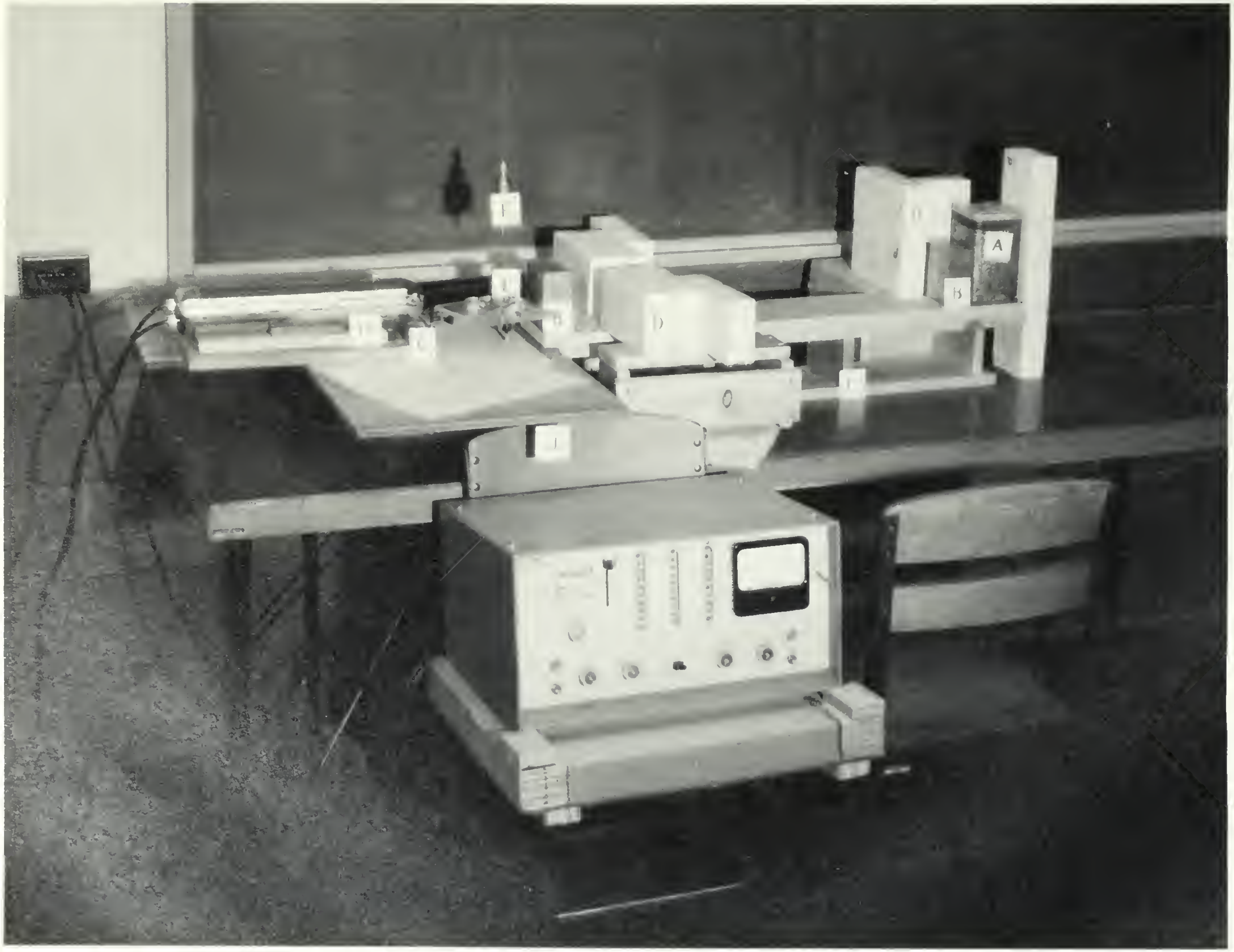
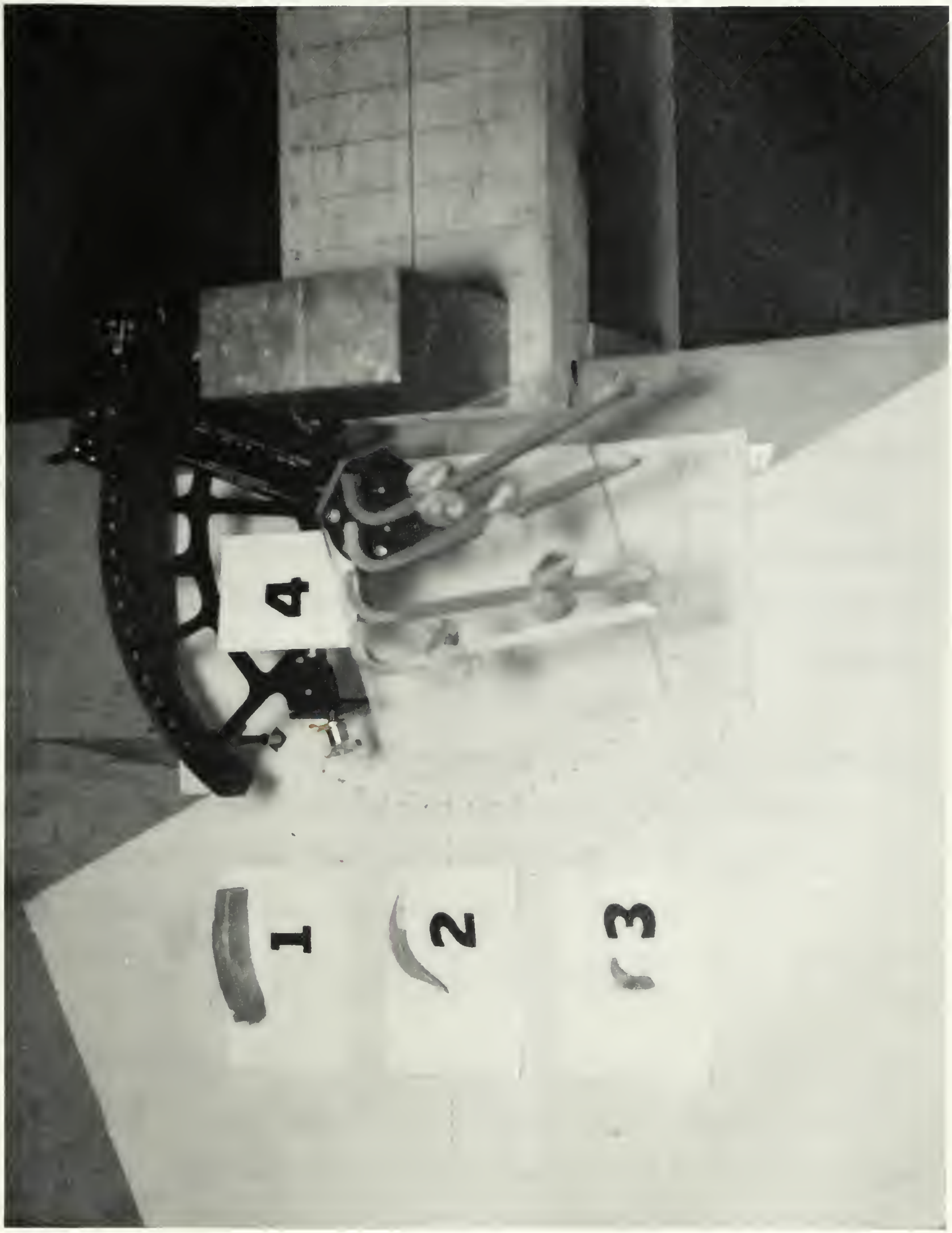

A
B

Figure 6. Experimental reflective elements.


1
2
3
4

diameter of one-half inch. Two steel set screws were set opposite each other on the circumference of the wafer to permit handling with a magnet and an aluminum extension with eyehole was attached to one face to permit handling the source from a distance with a cord.

The source container was made by casting lead into a commercial can with the dimensions 6.5 inches x 4 inches x 4 inches to a depth of 5.5 inches. To accomodate the source, a 3/4 inch hole was drilled to a depth of two and one-half inches so that the centerline of the hole was midway between the sides and parallel to the base of the container at a distance of two inches. On the same centerline, the remaining one and one-half inches were drilled with a 5/32 inch bit so that the source could be mounted in the container by passing the cord through and pulling it into place.

Dosage calculations were based on information taken from Glasstone (10) who has derived the dosage rate in milliroentgens per hours (mr/hr.) at a distance (d) cm. from a C curie unshielded point source as:

$$\text{Dose rate} = 5.2 \times 10^6 \frac{C\ E}{d^2} \text{ mr/hr.,} \qquad (6)$$

where the energy E is expressed in MEV/gamma ray photon. The derivation of this equation was based on the following assumptions: (1) source is a point source, (2) radiation emitted by this point source is emitted uniformly in all direc-

tions, (3) the energy absorption coefficient of air for gamma rays may be taken to have a constant value of 3.35×10^{-5} cm.$^{-1}$ over a range of gamma ray energies from 0.07 to 2 Mev. While this equation will yield results which are slightly on the unconservative side, it should result in an accuracy of ±10 per cent which is sufficient as long as one remains well below the maximum permissible dosage limits. If a collimated beam of intensity I_o passes through an absorber such as lead of thickness x, the intensity of the emergent beam I_x can be obtained from the expression given in Glasstone (10):

$$I_x = I_o e^{-\mu x}, \qquad (7)$$

where μ is defined as the linear absorption coefficient of the given absorber for a particular radiation. This relation is based on the assumption that the gamma radiation is monoenergetic, but one may accept the results of the application of it to Co-60 gamma radiation since the energies of the Co-60 gamma rays are not too vastly different (1.17 and 1.35 Mev.). From data given by Kaplan (11), a value for the linear absorption coefficient for lead for a gamma ray energy of 1.25 Mev. was taken to be equal to 0.66 cm.$^{-1}$. If it is desired, Equations 6 and 7 can be combined to give the dose rate at a distance d cm. from a C curie source with x cm. of absorber expressed by :

$$\text{Dose rate} = 5.2 \times 10^{6} \frac{CE}{d^2} e^{-\mu x} \qquad (8)$$

Equation 8 was used to calculate the dose rate on the surface of the source container with the following substitutions:

C = source strength in curies or 2.5×10^{-3} curies

E = 2 (1.25 Mev./photon) or 2.50 Mev. In its radioactive decay, Co-60 emits 2 photons of 1.17 and 1.33 Mev. which may be considered as 2 photons with an average energy of 1.25 Mev. for dose rate calculations

d = 1.625 inches = 4.13 cm. (from the dimensions of the source container)

$\mu = 0.66$ cm.$^{-1}$

x = 1.625 inches = 4.13 cm. (x and d are the same here since the dose rate is desired at the surface of the source container)

Substituting the values given above in Equation 8,

$$\text{dose rate} = \frac{5.2 \times 10^{6}(2.5 \times 10^{-3})(2.50)e^{-0.66(4.13)}}{(4.13)^{2}} =$$

$$124 \text{ mr/hr.}$$

The maximum permissible exposure on the hands and forearms is 1500 mr/week (10) and since it was not expected that the source container would be handled more than an hour throughout the entire course of the experimentation, this value of dose rate did not present any undue hazard. The maximum permissible dose rate for whole body exposure is limited to 300 mr/wk. and

calculations similar to those made above indicated that at a distance of 12 inches from the source container, the dose rate was reduced to 1.77 mr/hr., which is equivalent to 297 mr/wk., based on continuous exposure.

During the course of the experimentation, liberal use was made of shielding bricks which were placed about the source container to minimize the radiation in directions other than along the collimated beam. Periodic surveys of the working area and equipment made with a model 2612 Portable Survey Meter manufactured by the Nuclear Instrument and Chemical Corporation indicated that the operator was not exposed to a dosage rate greater than 0.5 mr/hr. at any time other than when required to handle the source container. Therefore, it was not considered necessary to wear an individual personnel monitoring device.

B. Collimators

The collimating blocks were made by casting a standard size 2 x 4 x 8 inch lead brick and cutting it in two to make two blocks of 2 x 4 x 4 inches. A 3/32 inch hole was then drilled through the two inch dimension at the center of the block. Since the assumption had been made earlier that a reasonable value for the critical angle for reflection was of the order of ten minutes, the decision was made to limit the

collimated beam to a cone of 20 minutes. This made it possible, theoretically, to have the entire collimated beam intercept parallel planes at the critical angle or less and still permitted enough radiation to reach the detector to obtain a reasonable degree of accuracy. From the geometry of the experimental arrangement, it can be easily shown that once having fixed the size of the collimated beam and the size of the cone of radiation desired, the collimating length was therefore fixed at 32.5 inches. A check of the efficacy of the collimators in reducing the radiation at the detector along lines other than the collimated beam was made using Equation 7. The total thickness of the two lead collimating blocks was four inches or 10.15 cm. The value of absorption coefficient was previously taken to be 0.66 cm.$^{-1}$ and one may express the fraction of the radiation which is allowed to pass through the blocks as:

$$\frac{I_x}{I_o} = e^{-\mu x}. \tag{9}$$

Substituting the values above into this equation, the result was obtained that the fraction of radiation which was allowed to pass through the collimating blocks in directions other than along the collimated beam was 0.00123. It was considered that this would be a sufficient reduction of the scattering radiation to permit the taking of accurate data.

C. Rotating Platform and Polar Grid

It has been postulated that the critical angle for reflection of gamma ray photons from several different materials is of the order of 5 - 10 minutes. To insure that a specimen could be aligned within these limits, a sextant was adapted for use as a rotating platform upon which the specimens could be placed as shown in Figure 6. The sextant was a recent model used by the U.S. Navy and manufactured by the Bendix Aviation Corporation. Details of the operation of the sextant will not be attempted here since the instrument was used solely as a specimen platform which could be rotated through angles of 0.1 minutes with a probable accuracy of plus or minus one-tenth of a minute. To accomodate specimens up to 6 inches in length, a plexiglass platform was designed to be fixed in place over the center of rotation of the sextant arm. The transparency of the plexiglass permitted the operator to mount a specimen for reflection directly over the center of rotation of the arm so that rotation of the arm did not translate the specimen with respect to the incident gamma ray beam but merely rotated the incident face. The limits through which the platform could be rotated were determined by the arrangement of the apparatus in that it was desirable to keep the total distance of source to detector to a minimum, hence the platform and specimen were placed as close to the second collimating block as possible. The sextant was rigidly fixed in position

so that the center of rotation over which the incident face of the specimens were to be mounted was 1 7/8 inches from the collimating block. This permitted a rotation of the platform through a sector of 24 degrees which made it necessary to align the specimens only within plus or minus 10 degrees.

With the specimen set as desired relative to the collimating beam, it was necessary to have some means of measuring the gamma radiation at various points around the sample in order that a tendency for reflection might be detected. For this purpose, a polar coordinate grid was mounted on the platform supporting the sextant as shown in Figure 6 such that the center of the grid was located beneath the center of rotation of the specimen platform and the zero degree position was aligned with the collimated beam. An extension of the radii permitted positioning of the detector at selected distances from the center of rotation between the limits of 7 and 11 inches. Measurements were taken at various intervals from -30° to +60° with the positive angles being taken in the quadrant in which it was expected that reflected gamma radiation would appear.

Although it would have been desirable to fix the detector rigidly to a point on the axis of rotation of the specimens, the equipment did not lend itself readily to this type of arrangement and indeed it was not desired since it would have made it too difficult to reposition the detector without jarring the specimen platform. The detector was, therefore,

positioned manually using scribe marks drawn on the polar grid which were measured from the origin for the lineal measurement and a thin rubber band which was fixed below the center of rotation of the specimens on one end and on the other end fixed directly beneath the detector face for the angular measurement. It was estimated that this arrangement permitted an accuracy of plus or minus 1/32 of an inch for the lineal measurement and plus or minus 1/4 of a degree for the angular measurement.

D. Detector and Platform

The detector used throughout the experimentation was a Model DS-1A Scintillation Detector manufactured by the Nuclear Instrument and Chemical Corporation. This detector was designed for use where greater efficiency was desired in the detection of gamma radiation than is possible using Geiger-Mueller detectors and was supplied with a removable directional shield which provided sharp discrimination against activities more than 15 degrees off the axis of the probe. With this directional shield the detector had a published efficiency of 33 per cent for Co-60 gamma rays. The counting rate of this instrument was limited by the RC time constant of the preamplifier so that signal events spaced closer than 2-3 microseconds could not be resolved. Since the scalar used had a

published resolving time of 5 microseconds, the scalar was the controlling instrument in the determination of coincidence loss. Further comment will be made on this in the following section.

The external directional shield had an aperture of one inch which intercepted an included angle of approximately 5.2 degrees when positioned 11 inches from the center of rotation of the specimens. Therefore a slight overlap of data occurred when the detector was moved only 5 degrees. This was not considered detrimental as long as the method of obtaining the gamma radiation survey around the sample was consistent.

The detector platform was fashioned from two segments of wood in such a manner that the detector could be rotated through any desired angle while the base of the platform was kept at a fixed position on the polar grid. This was designed in this manner to permit some flexibility in the positioning of the detector should it be desired during the course of the experiment. In actual practice, the entire unit was fixed with the detector directed at an extension of the axis of rotation of the specimens which was determined by means of a plumb positioned directly over the axis of rotation.

E. Scalar

A Model 181A Decade Scalar manufactured by the Nuclear-Chicago Corporation was used in conjunction with the scintil-

lation detector described above. The coincidence loss of the system as a whole was determined by the resolution time of the scalar. According to information given by the manufacturer, the resolution time for the scalar used was 5 microseconds which is a function of the operation of the first decade. To determine whether a resolving time or dead time of this magnitude resulted in a significant loss of counts per unit time, use was made of the following equation given by Friedlander and Kennedy (12):

$$R^{*} = \frac{R}{1 - R\tau} \tag{10}$$

where R^{*} is the rate that would be recorded if there were no coincidence losses.

R is the observed counting rate, and τ is the resolving time or dead time, equal to 5 microseconds in this case. The maximum counting rate observed in the course of the experimentation was 1950 cpm. (32.5 cps.). Substituting these values into Equation 10 R^{*} was found to be 32.5053 to six significant figures. Since this amounts to an increase of less than 0.02 per cent, the correction was considered to be negligible and therefore not applied to the data which were taken.

F. Auxiliary Apparatus

All the equipment used with the exception of the scalar was mounted on a unit platform which is shown in Figure 5. The platform was constructed so that the detector, the specimens, the collimators, and the source were all on the same horizontal plane and gave the entire arrangement a rigidity which it would not have had had the separate units been arranged on a table or laboratory bench.

A mechanical timer (stopwatch) was used throughout the experiment which was calibrated in units of 0.01 minutes. To eliminate any possible variation in timing from one run to another, the stopwatch was wound fully prior to the timing of each count.

V. METHOD OF PROCEDURE

The experimental procedure in general terms consisted of choosing the specimen to be checked for reflective properties, aligning the specimen on the rotating platform so that the platform could be rotated in increments of five seconds or less through an angle which was certain to include the critical angle for reflection, determining the position of the specimen which allowed the collimated gamma ray beam to be incident at the critical angle or less and, finally, conducting a survey of the gamma radiation about the specimen.

Although a sharply defined reflected beam would have represented optimum results, this was not expected for several reasons. Compton (3a) has given curves of the intensity of reflection versus the critical angle required for reflection for x-rays with various materials which indicate that the reflected intensity decreases gradually as θ is increased from zero angle of incidence to a value approaching the critical angle. The curves are continuous and decrease more rapidly as the critical angle is approached, beyond which the reflected intensity is virtually zero. Therefore, one would not expect to obtain 100 per cent reflection nor would one expect that the critical angle would be sharply defined. In addition to this consideration, bending of the zinc crystals did not result in a specimen in which all planes were parallel and curved through the same number of degrees of arc. This would lead one to

suspect that some reflection would occur through an infinite variety of angles, hence a broad spectrum of reflection would be obtained rather than a sharply defined beam. The initial postulate of gamma ray reflection was based on the premise that a photon would continue a reflective cycle once begun throughout the curvature of the plane but this postulate ignored the possibility of scattering interactions and assumed that the element consisted of perfect curved elements. Since the zinc crystals which were used were known to contain imperfections and since it was understood that the scattering interaction could not be ignored, the results expected were based on the idea that some gamma rays might reflect a number of times from a curved element before scattering out of the material, while others might simply scatter and not have an opportunity to even begin a reflective cycle. While the possibility of obtaining results which indicated a narrow spectrum of reflection was not rejected, all the considerations mentioned above appeared to point more strongly to a broad band of reflected radiation.

Initially, the method of procedure was to obtain two kinds of data. One set of data was to be a measurement of the gamma radiation detected through a 90° arc of a circle (with a radius of 7 inches and centered under the axis of rotation of the specimen platform) before a proposed reflective type specimen was placed incident to the collimated beam. This data then was to serve as an initial condition to which one could compare

the reflective measurements taken on subsequent runs. It was expected that the reflective data would then be revealed either by a shift in the counting rate peak in the direction in which reflection was expected or a tendency for the counting rate to level off slightly rather than decrease abruptly. Both these conditions would be evident when a comparison was made with the unreflected data. This was done with specimens 1 and 2 with all the measurements of counting rate being taken with the detector at 7 inches from the center of rotation.

Midway through the experimentation, the method of procedure was changed in an attempt to obtain more definite indications of reflection. It was postulated earlier that the percentage of incident photons which were reflected would be very small and that those photons which were reflected would do so through an infinite number of angles. If this were so, then comparison of the reflected data with that of the unreflected data could possibly fail to show any of the results desired. Therefore, the decision was made to obtain the reflected data as before and then to rotate the crystal through an angle such that the collimated beam was no longer incident to the planes at the critical angle and measure the counting rate for this condition. Then, if both sets of data were plotted on one curve, small differences in counting rate would be observed readily with a resultant simplification in the analysis of the data. This method of procedure was followed with specimens 3 and 4.

The most difficult portion of the experiment was undoubtedly that of aligning the specimens such that the collimated beam was incident to the curved planes at the critical angle or less. Since the reflection was expected over a large number of degrees and was expected to be a small percentage of the incident photons, it was not reasonable to expect that an increase in counting rate would be observed at any particular position as the specimen was rotated through the critical angle unless the length of count was long enough to eliminate most of the statistical variation. However, if the detector was kept at the zero degree position (aligned with the specimen, collimators, and source) while the specimen was rotated through the critical angle, then a reflection of the incident photons through any angle not included in the field of the detector would cause the counting rate to decrease. In order to narrow the sector included in the field of the detector, the scintillation detector was positioned 11 inches from the center of rotation, which was the maximum distance permitted by the apparatus as designed. In this position, the angle included by the detector was only 5.2 degrees so that any portion of the gamma radiation which was reflected through an angle greater than 2.6 degrees would escape detection and the counting rate would decrease.

With the rotating platform set at its mid-angle, the specimen chosen was aligned so that the collimated beam was incident to the reflective planes, with a probable error of

less than ±5°. The specimen was then fastened to the platform with clay and the platform was rotated about 10° whereupon it was obvious that the specimen was no longer aligned as required for reflection. The platform and specimen together were then rotated through increments of 5 minutes in the opposite direction and the counting rate recorded with each new angle set. This was done for a total of 20° to insure that the specimen had been rotated through the critical angle. The resultant data were then plotted as the counting rate versus the angular position of the specimen and the position at which the least counting rate was observed was taken to be the optimum position for reflection.

Then, with the specimen set at this optimum position for reflection, the detector was rotated about the specimen in 5 or 10 degree increments from 30° on one side of the collimated beam to 60° on the other, with the counting rate being recorded at each position. As a means for comparison, the specimen was then rotated through an angle of 10° so that the planes were definitely not aligned with the collimated beam and the counting rates recorded at the same detector positions as before. These data should then have been the results of scattering only and should have taken out the component of reflected radiation which was present in the first set of data. Again, this was the procedure followed with specimens 3 and 4.

In order to restrict the length of time required to ob-

tain the experimental data, it was necessary to accept a standard deviation such that the per cent error for a given counting rate would not be significantly greater than two per cent. Friedlander and Kennedy (12) have shown that the standard deviation σ is related to the total count m and the length of observation t in the following manner:

$$\sigma = \frac{\sqrt{m}}{t} . \tag{11}$$

An estimate was then made of the counting rate which was expected and substituting this into the relation given above, it was decided that an observation time of 10 minutes would yield results which would be accurate within two per cent error, based on a 68 per cent confidence level.

VI. RESULTS

The results of the experimentation have been presented in tables and graphs in two general forms. For specimens 1 and 2, the reflected data were to be compared to the data taken with no reflecting specimen in place and an analysis made on the basis of a possible shift in the peak gamma radiation, or a change in slope (counts per minute versus angular position) as the detector was rotated about the specimen, or perhaps a small increase in counting rate at a detector position well off the centerline. For this analysis, it was not considered necessary to plot and record the net counting rates obtained but rather it was desired to indicate the background observed and then compare the results of total counting rate versus detector position. With this in mind then, Table 2 shows the data obtained for an initial condition with no reflecting specimen in position. R_t and σ_t represent the total counting rate observed and the standard deviation for that counting rate, respectively. Figure 7 is a plot of the data of Table 2 with the background activity indicated as a cross-hatched band to show the deviation.

The first specimen to be tested for reflective properties was specimen 1, the copper electrodeposited curved element. Table 3 is a tabulation of the counting rate observed versus the detector position when the specimen was aligned for reflec-

Table 2. Gamma survey with no reflecting specimen in place

Detector position degrees	Total count	Length of count min.	R_t cpm.	σ_t cpm.
Background	3045	10	304.5	
-30	4154	10	415.4	6.5
-20	4233	10	423.3	6.5
-10	7068	10	706.8	8.4
- 5	10450	10	1045.0	10.2
0	19496	10	1949.6	14.0
5	11400	10	1140.0	10.7
10	7190	10	719.0	8.5
20	4549	10	454.9	6.8
30	3818	10	381.8	6.2
40	3843	10	384.3	6.2
45	3263	10	326.3	5.7
50	3302	10	330.2	5.8
60	3227	10	322.7	5.7

tion. As before, the standard deviations are also tabulated for the total counting rate observed. These data are plotted in Figure 8 in the same manner and to the same scale as the data of Figure 7.

Table 4 is a tabulation of the data obtained with speci-

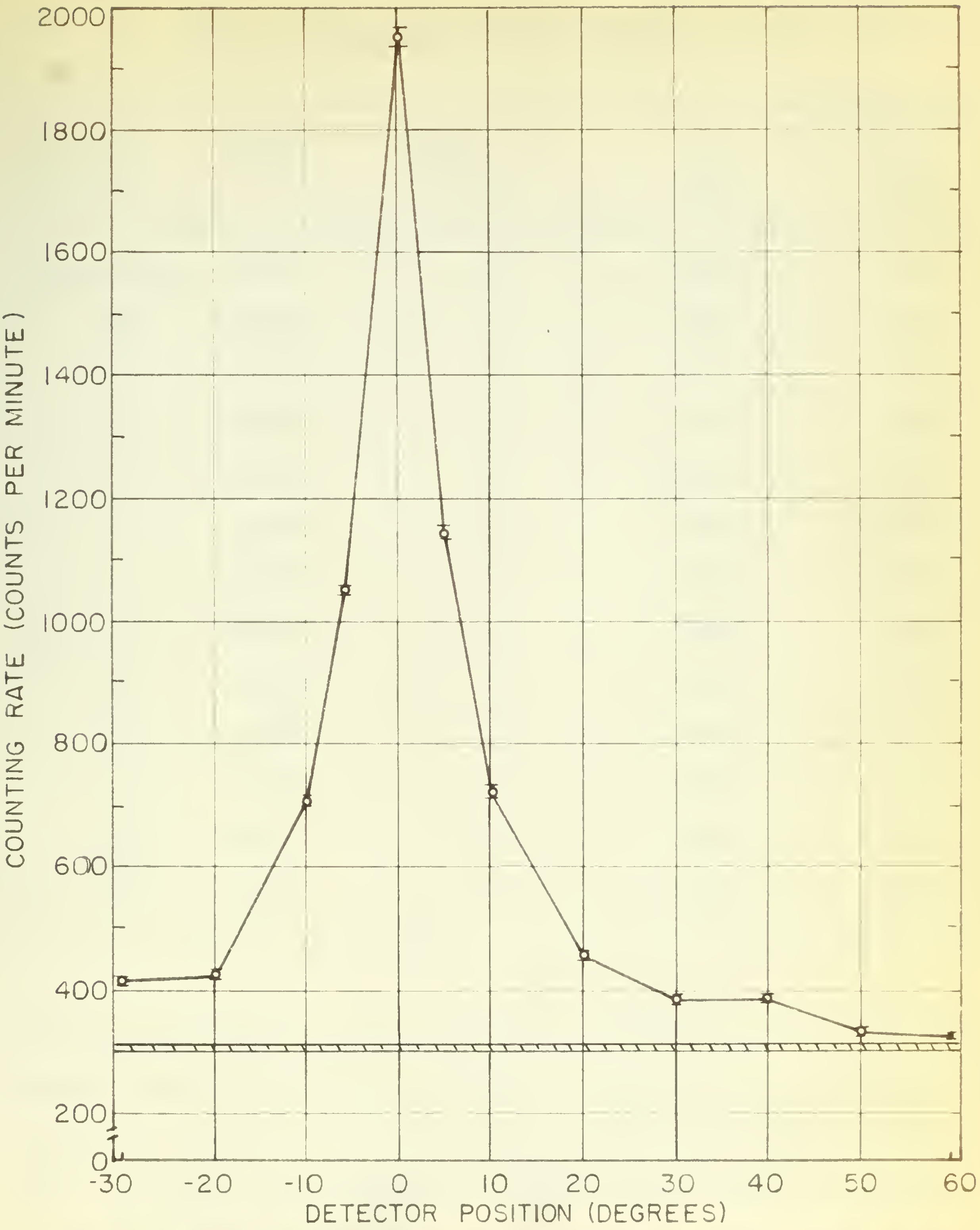


Figure 7. Gamma survey with no specimen in place (unreflected)

Table 3. Gamma survey for reflection using specimen number 1, copper electrodeposited specimen

Detector position degrees	Total count	Length of count min.	R_t cpm.	σ_t cpm.
Background	3376	10	337.6	5.8
-30	2222	5	444.4	9.4
-20	2077	5	415.4	9.1
-10	3847	5	769.4	12.4
- 5	5672	5	1134.4	15.1
0	4548	5	909.6	13.5
5	4309	5	861.8	13.2
10	3707	5	741.6	12.0
20	2309	5	461.8	9.6
30	2136	5	427.2	9.2
40	1912	5	382.4	8.7
50	1811	5	362.2	8.5
60	1819	5	363.8	8.5

men 2, a portion of a zinc crystal in which the individual basal planes were bent through an angle of approximately 20° while the segment of crystal as a whole was bent through approximately 60°. The data are plotted in Figure 9 in the same manner as the previous sets of data.

The remainder of the data which is tabulated in Tables 5,

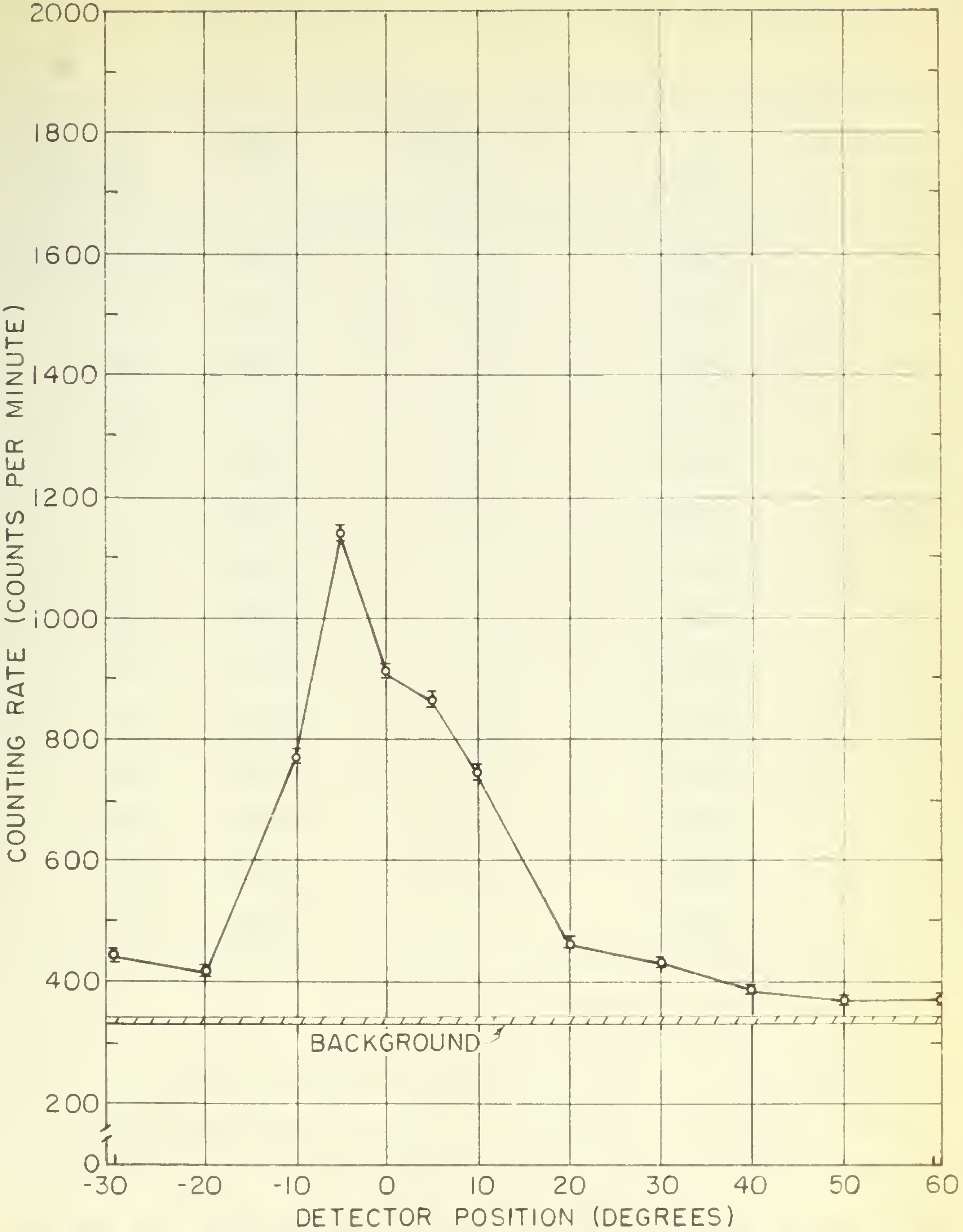


Figure 8. Gamma survey with copper electrodeposited specimen.

Table 4. Gamma survey for reflection using specimen number 2, zinc crystal

Detector position degrees	Total count	Length of count min.	R_t cpm.	σ_t cpm.
Background	3036	10	303.6	5.5
-30	4119	10	411.9	5.3
-20	3716	10	371.6	6.1
-10	4169	10	416.9	6.5
- 5	9945	10	994.5	10.0
0	14285	10	1428.5	12.0
5	9087	10	908.7	9.5
10	4957	10	495.7	7.0
15	4269	10	426.9	6.5
20	4323	10	432.3	6.6
30	3558	10	355.8	6.0
40	3366	10	336.6	5.8
50	3146	10	314.6	5.6
60	3207	10	320.7	5.7

6, 7, and 8 and plotted in Figures 10 and 11 are presented in a slightly different manner. In order to compare the curves which in theory represented reflective data and scattering data, it was deemed desirable to plot them on the same graph. Since the values of background activity changed somewhat, it was

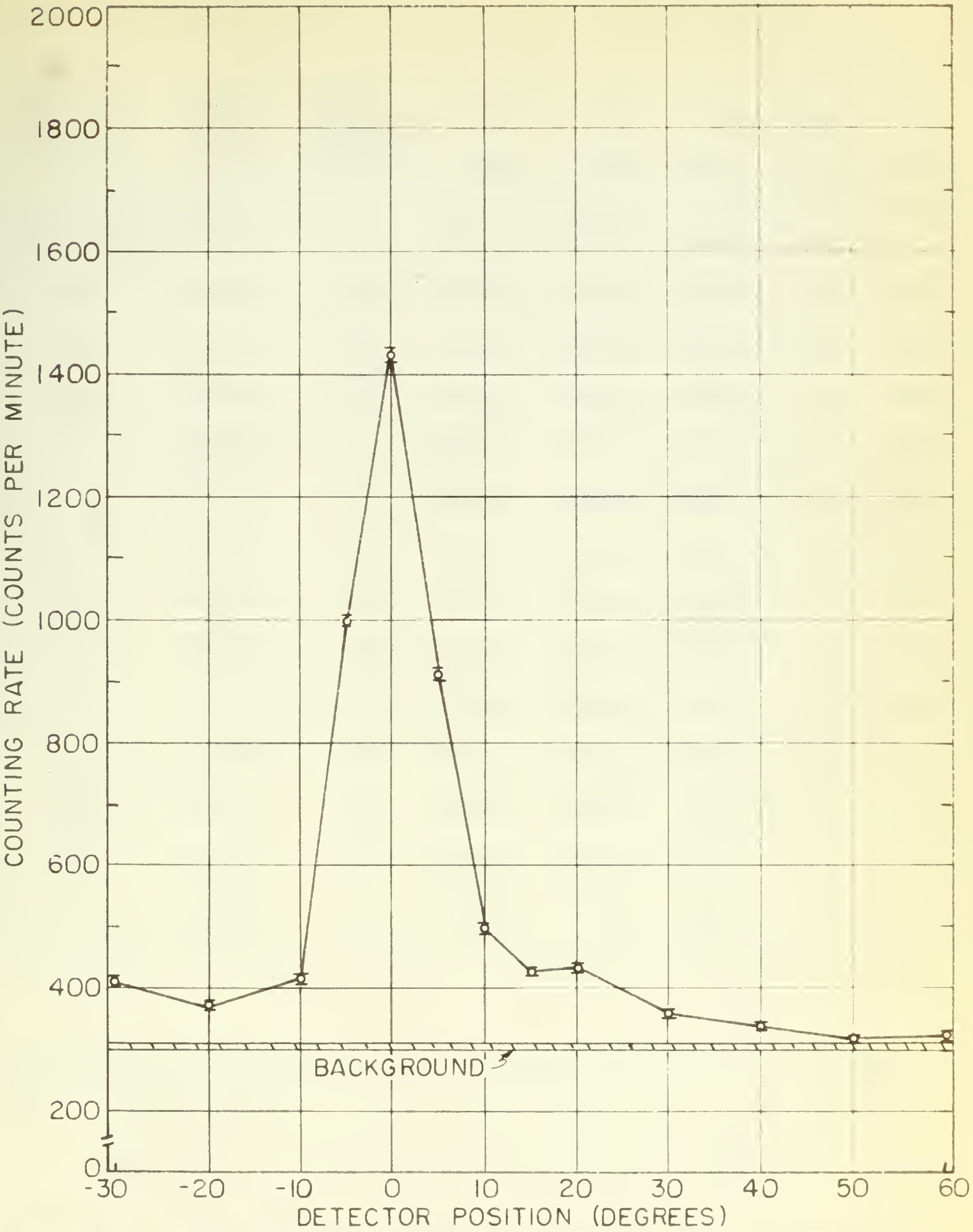


Figure 9. Gamma spectrum with specimen 2, zinc crystal.

Table 5. Gamma survey, specimen 3, reflection data

Detector position degrees	Total count	Length of count min.	R_t cpm.	R_b cpm.	R_n cpm.	σ_t cpm.	σ_n cpm.
Background	2512	10	251.2	251.2	251.2	5.0	
-30	4171	10	417.1	251.2	165.9	6.5	8.2
-20	3845	10	384.5	251.2	133.3	6.2	7.9
-10	6150	10	615.0	251.2	363.8	7.9	9.4
- 5	10582	10	1058.2	251.2	807.0	10.2	11.3
0	15374	10	1537.4	251.2	1286.0	12.4	13.4
5	8972	10	897.2	251.2	646.0	9.5	10.7
10	5949	10	594.9	251.2	343.7	7.7	9.2
15	4863	10	486.3	251.2	235.1	7.0	8.6
20	4032	10	403.2	251.2	152.0	6.4	8.1
30	3504	10	350.4	251.2	99.2	5.9	7.7
40	3084	10	308.4	251.2	57.2	5.6	7.5
50	2989	10	298.9	251.2	47.7	5.5	7.4
60	2849	10	284.9	251.2	33.7	5.3	7.3

necessary to compute the net counting rates and net values of the standard deviation to make the comparisons more meaningful.

Table 5 is a tabulation of the data obtained with specimen 3, a curved zinc crystal in which the basal planes were bent through an angle of approximately 60° while the crystal,

Table 6. Gamma survey, specimen 3, scatter data

Detector position degrees	Total count	Length of count min.	R_t cpm.	R_b cpm.	R_n cpm.	σ_t cpm.	σ_n cpm.
Background	2512	10	251.2	251.2	251.2	5.0	
-30	3988	10	398.8	251.2	147.6	6.3	8.0
-20	3660	10	366.0	251.2	114.8	6.1	7.9
-10	6233	10	623.3	251.2	372.1	7.9	9.4
- 5	9673	10	967.3	251.2	716.1	9.9	11.1
0	15813	10	1581.3	251.2	1330.1	12.6	13.5
5	8683	10	868.3	251.2	617.1	9.3	10.6
10	5977	10	597.7	251.2	346.5	7.7	9.2
15	4745	10	474.5	251.2	223.3	6.9	8.5
20	3958	10	395.8	251.2	144.6	6.3	8.0
30	3585	10	358.5	251.2	107.3	6.0	7.8
40	3168	10	316.8	251.2	65.6	5.6	7.5
50	3051	10	305.1	251.2	53.9	5.5	7.4
60	2846	10	284.6	251.2	33.4	5.3	7.3

as a whole, was bent through approximately 90°. As before, R_t represents the total counting rate observed and σ_t is the standard deviation calculated for that counting rate. R_b represents the value of the background activity observed and R_n represents the net counting rate which was taken as R_t -

Table 7. Gamma survey, specimen 4, reflection data

Detector position degrees	Total count	Length of count min.	R_t cpm.	R_b cpm.	R_n cpm.	σ_t cpm.	σ_n cpm.
Background	1762	10	176.2	176.2	176.2	4.2	
-30	4231	10	423.1	176.2	246.9	6.5	7.7
-20	3755	10	375.5	176.2	199.3	6.1	7.4
-10	6419	10	641.9	176.2	465.7	8.0	9.0
- 5	10383	10	1038.3	176.2	862.1	10.2	11.0
0	10122	10	1012.2	176.2	836.0	10.1	10.9
5	7876	10	787.6	176.2	611.4	8.9	9.8
10	5560	10	556.0	176.2	379.8	7.5	8.6
15	4963	10	496.3	176.2	320.1	7.1	8.2
20	4086	10	408.6	176.2	232.4	6.4	7.7
30	3631	10	363.1	176.2	186.9	6.0	7.3
40	3250	10	325.0	176.2	148.8	5.7	7.1
50	3026	10	302.6	176.2	126.4	5.5	6.9
60	2918	10	291.8	176.2	115.6	5.4	6.8

R_b. The net standard deviation σ_n was computed as the square root of the sums of the squares of the deviation for the background counting rate and the observed counting rates or in symbols,

Table 8. Gamma survey, specimen 4, scattering data

Detector position degrees	Total count	Length of count min.	R_t cpm.	R_b cpm.	R_n cpm.	σ_t cpm.	σ_n cpm.
Background	1754	10	175.4	175.4	175.4	4.2	
-30	4258	10	425.8	175.4	250.4	6.5	7.8
-20	3834	10	383.4	175.4	208.0	6.2	7.5
-10	6235	10	623.5	175.4	448.1	7.9	8.9
- 5	9879	10	987.9	175.4	812.5	9.9	10.8
0	10765	10	1076.5	175.4	901.1	10.4	11.2
5	7665	10	766.5	175.4	591.1	8.8	9.7
10	5607	10	560.7	175.4	385.3	7.5	8.6
15	5171	10	517.1	175.4	341.7	7.2	8.3
20	3860	10	386.0	175.4	210.6	6.2	7.5
30	3426	10	342.6	175.4	167.4	5.9	7.2
40	3032	10	303.2	175.4	127.8	5.5	6.9
50	2957	10	295.7	175.4	120.3	5.4	6.9
60	2394	10	239.4	175.4	64.0	4.9	6.4

$$\sigma_n = \sqrt{\sigma_{t_b}^2 + \sigma_t^2} \quad , \qquad (12)$$

where

σ_{t_b} = standard deviation of the observed background counting rate

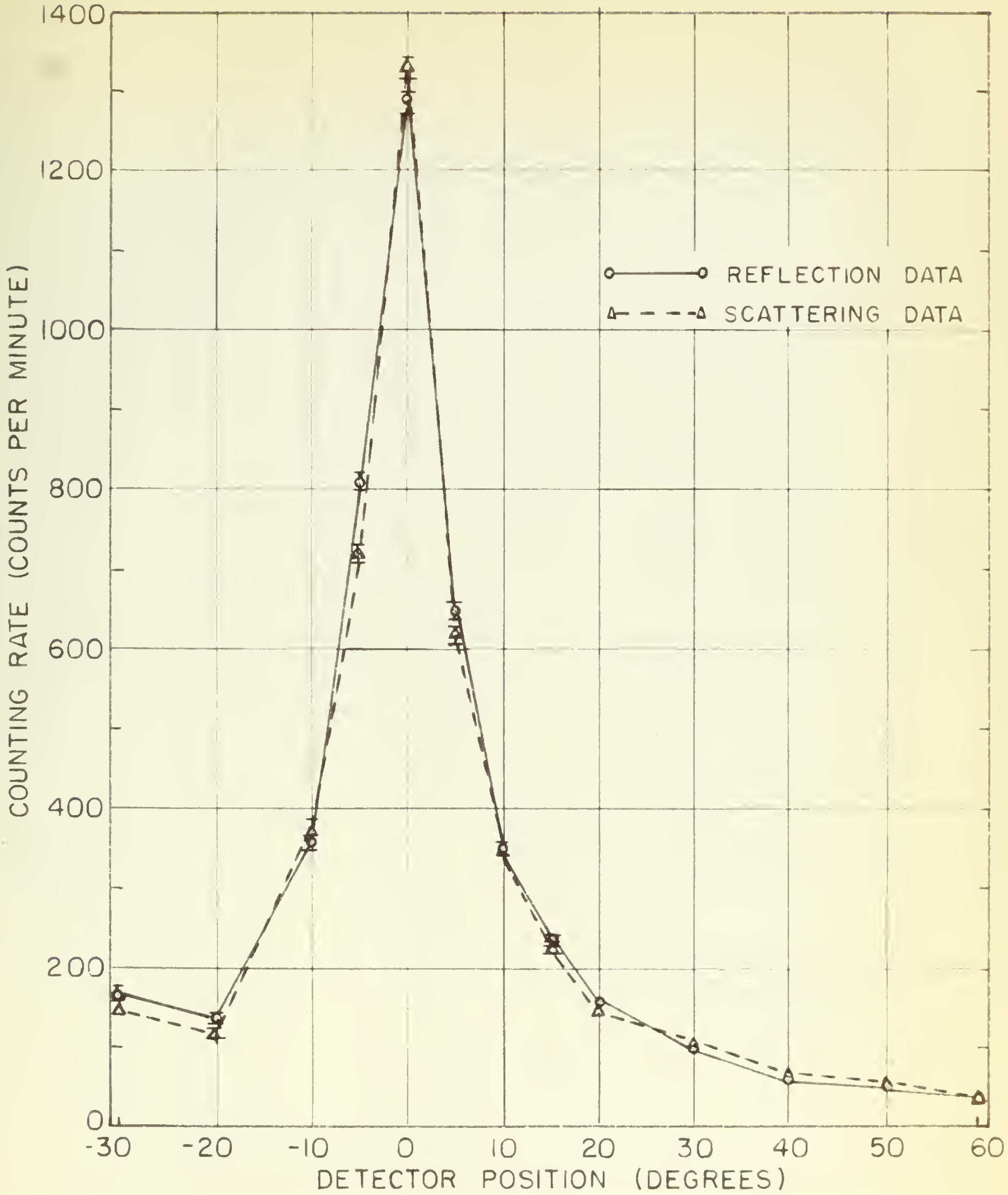


Figure 10. Gamma survey about specimen 3, zinc crystal, with reflection data and scattering data superimposed.

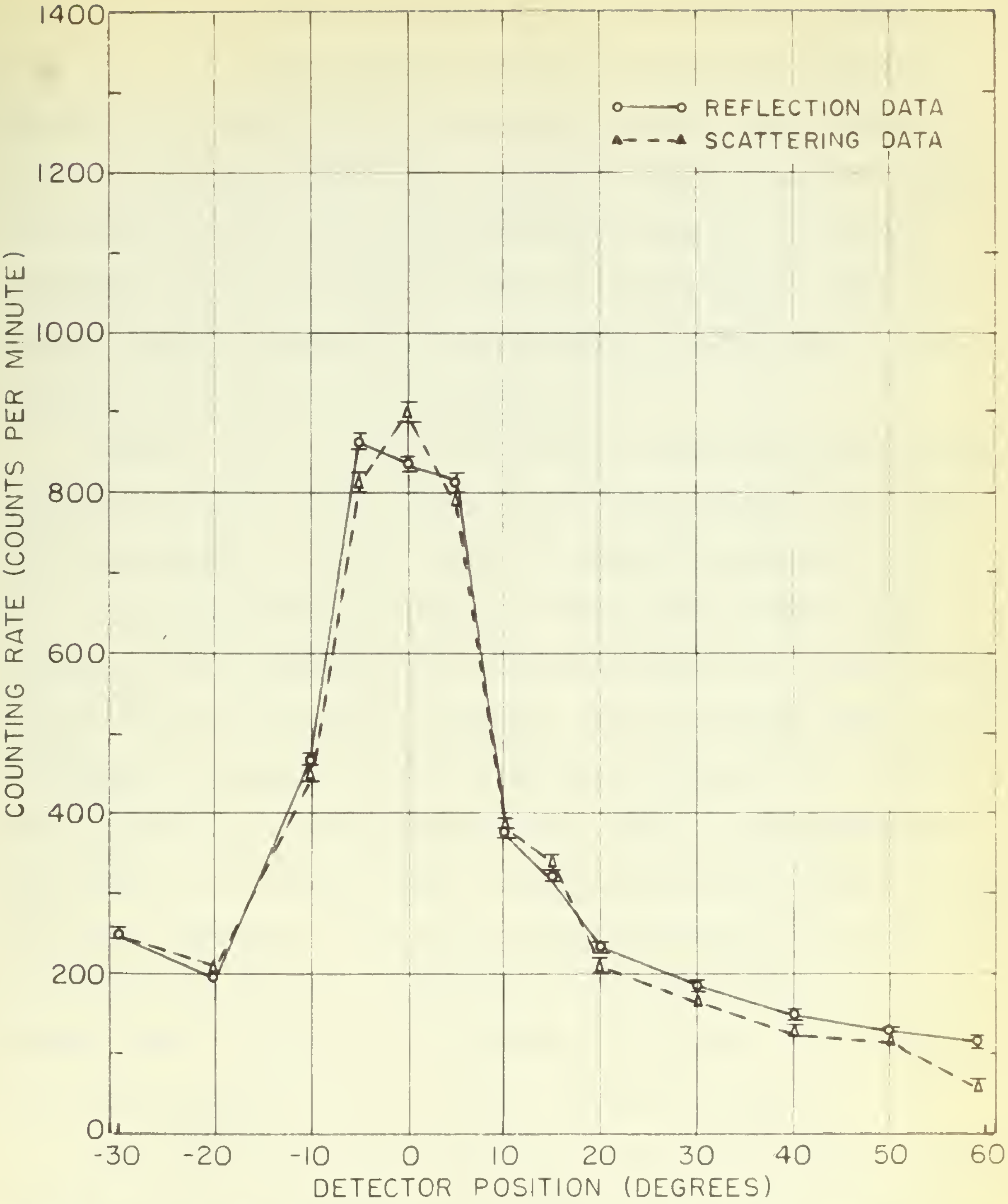


Figure 11. Gamma survey about specimen 4, four zinc crystals, with reflection and scattering data superimposed.

σ_t = standard deviation of the observed counting rate for each individual detector position.

Table 6 is a tabulation of the data obtained with the same specimen as above after the crystal had been rotated through an angle of 10° so that the collimated beam was no longer incident to the reflective planes at the critical angle or less. The data from both these tables (5 and 6) are plotted in Figure 10 for ease in comparison.

Tables 7 and 8 are a tabulation of the same type of data as just described with four zinc crystals aligned for reflection (specimen 4) and the data are plotted in Figure 11.

The data which were obtained during the initial positioning of the specimens for reflection have not been included in the report for several reasons. The specimens were rotated through approximately 20° in 5 minute increments and a count was taken at each new position for a total of approximately 240 values of counting rate for each specimen mounted. It was felt that these data were excessively voluminous and would not contribute anything of significance to the report since it served only to orient the specimens and did not lend itself to a determination of the critical angle involved.

The data which were obtained in the latter portion of the experimentation involved a comparison of two sets of data in which small differences were rather significant. In order to avoid any possible variation in the application of a smooth curve to the data such that it would tend to improve or detract

from the results obtained, it was felt that the use of straight lines to join the individual points would allow a more honest evaluation of the results. For the sake of continuity then, this was done in the presentation of all the results.

VII. DISCUSSION

In order to evaluate the results obtained with the first two reflective specimens, the initial condition which illustrates the gamma radiation pattern before a reflective specimen was placed in the apparatus must be examined closely. This is given in Figure 7 with a tabulation in Table 2. One would normally expect that the radiation pattern would be symmetrical about the collimated beam which in every case was taken to be along the zero degree position of the detector. In addition, one would expect a rather narrow band of radiation which would drop off rapidly as the detector was moved off the axis of the collimated beam since the collimators were designed to yield a cone of 20 minutes. The broadness of the band of radiation which was obtained can be explained by a consideration of the scintillation detector. For this data, the detector was positioned 7 inches from the center of rotation of the rotating platform so that its one inch aperture included an angle of approximately 8.2 degrees. In addition to this, the detector was designed to discriminate sharply against radiation only if it were more than 15° off the axis of the probe. Since the collimated beam was quite narrow, the conclusion was drawn that the broadness of the peak intensity was due entirely to the characteristics of the detector. Had the apparatus been designed for collimation at the detector, this

would have been avoided but would have made the experimentation more difficult in view of the necessary repeated movements of the detector. Since all the data were taken under the same conditions, it was felt that final results would be unaffected by this characteristic of the measurements. The slight lack of symmetry which was recorded was probably due in part to statistical variation and in part to slight errors on the part of the operator in positioning the detector.

The data obtained with the electrodeposited copper specimen aligned for reflection are tabulated in Table 3 and plotted in Figure 8. The problem of alignment of this specimen in a favorable position for reflection to occur was the most difficult of all the specimens since no really definite decrease in counting rate was observed as it was rotated through 5 minute increments. On the basis of the data obtained, a "most likely" position for reflection was set and a survey made of the radiation about the element as given in Figure 8. It was noted that the peak intensity of the radiation leaving the specimen had shifted from the centerline of the collimated beam to a point 5° to the left of the beam as one views the source from the detector. This deflection was in a direction opposite to that which was expected since all the specimens had been curved and mounted so as to cause the incident radiation to reflect into the positive angle sector or to the right of the collimated beam. The conclusion which was drawn here

was that the shift in maximum intensity of the radiation was due entirely to scattering. The non-symmetrical pattern can be explained by noting that the specimen was curved into the positive quadrant, hence, at plus 5° the photons had to scatter through approximately 40 per cent more material than at -5° and had more opportunity to spread over a broader sector. The remainder of the curve outside of the plus to minus 5° sector shows little variation from the initial condition with no reflection except for the slight increase in counting rate observed at -30 degrees. This was attributed to scattering from a wall which was located on the left side of the apparatus. An increased counting rate at this position was noted with each specimen throughout the experiment and was in every case attributed to scattering from the wall. To avoid repetition, no further comment will be made on this point in the subsequent data.

The data which were obtained using the zinc crystal (specimen 2) are tabulated in Table 4 and plotted in Figure 9. Comparison of this data with the initial condition brought up the following observations: the intensity of the gamma radiation on the centerline was decreased by 27 per cent; the decrease in counting rate was not as sharp when the detector was moved off the centerline as in the initial condition, and a small but definite increase in counting rate was observed at +20°. The decrease in counting rate at the centerline was attributed to Compton scattering which accounts for approximately 99 per cent

of the gamma interactions in zinc at this energy as determined by Davisson and Evans (13). If one could substantiate the theory of reflection of the radiation, then a portion of this decrease in counting rate could be attributed to the reflection of the photons through an angle such as to escape detection with the detector at the center position. The slight broadening of the radiation pattern about the centerline can be explained by noting that the same condition exists here as did with the copper specimen; that is, scattered radiation need pass through less material to reach the detector when it is set at the -5° position than when it is set at the +5° position. It was noted, however, that the large discrepancy present with the copper specimen between the counting rates at these two positions was not evident here and this was taken to indicate that some photons might have been reflected through small angles so that they were detected at +5°. Unfortunately, not enough evidence exists to make this statement more positive. The slight increase in the counting rate at the +20° position might also be explained by concluding that it is the result of reflected photons but again the evidence was rather scanty and certainly not conclusive when one considers that the data are based on a 68 per cent confidence level. However, on the basis of the data obtained, the conclusion was drawn that a tendency for reflection did exist but that a more positive means for comparison was required since the percentage of incident gamma rays which were reflected seemed to be rather small.

As described earlier, it was suspected that a comparison of reflected data versus scattered data from a single specimen would yield more positive results, and the remainder of the experimental data was taken with this in mind. The next specimen chosen for analysis was a small segment of a zinc crystal (specimen 3) approximately one inch in length which was bent to a radius of curvature of 2.38 cm. so that the basal planes were curved through an angle of approximately 60°. The data obtained with this crystal aligned for reflection are tabulated in Table 5 and plotted in Figure 10. The rotating platform and crystal were then rotated counter-clockwise as a unit through an angle of 10° so that the collimated beam was no longer incident at the critical angle or less. The data obtained with the crystal in this position are tabulated in Table 6 and plotted in Figure 10. The curves of Figure 10 show a decrease in the counting rate on the centerline of the order of 3.3 per cent with the crystal aligned for reflection as opposed to scattering. This would lead one to suspect that some of the incident radiation was reflected through an angle and thereby escaped detection at the zero degree position. With this hypothesis, one would next assume that the reflected photons would appear in the positive quadrant and would be observed as a general increase in the counting rate over the curve for scattering. As expected, the curves do show that an increase in counting rate was present when the crystal was

aligned for reflection from +4° to +25° and this was interpreted as a rather definte indication that a small percentage of the incident photons had indeed been reflected through large angles. The increase in the counting rate when the detector was set at the -5° position can perhaps best be explained by showing the relation of the basal planes to one another in the crystal after bending. If one inscribes a series of parallel lines on the edge of a deck of cards such that the planes containing these lines are perpendicular to the edge and make an angle of 30° with the planes parallel to the face of the cards, a rather crude but effective representation has been made of the orientation of the basal planes in the zinc crystals which were used. If one then bends these cards about some cylindrical object and observes the lines which represent the basal planes, it will be seen that the planes are no longer parallel because they have slipped as they were bent. Now aligning one's sight so that it is tangent to the leading edge of mid-plane, one can see that while most of the planes are curved to one side of the line of sight, some of the planes are curved so that they would reflect photons in the opposite direction. This is what has been postulated for the arrangement of the planes in the crystal and the increased counting rate at -5° is then explained by the theory that some of the scattered photons intercepted the planes which were curved initially into the negative sector and reflected through a portion of the arc of the planes until they were scattered out

of the material. The increased counting rate from -20 to -30° results as before from scattering from the wall and is greater for the reflective case since more photons were reflected into the negative sector than in the scattering condition.

On the basis of these results, a means was sought which would increase the percentage of the photons reflected and substantiate the theory more effectively. To accomplish this, an attempt was made to align four crystals on the rotating platform together to increase the number of basal planes from which the photons could reflect. Each of the four crystals was bent to a radius of curvature of 1.0 inches so that the basal planes were curved through an angle somewhat greater than 60° and the crystals themselves through approximately 120 degrees. They were then aligned one behind another as shown in Figure 6. Unfortunately the nature of the experimental arrangement did not permit the operator to align each individual crystal in such a manner that its planes were properly oriented for reflection to occur. For this portion of the experiment, it was necessary to be content with a manual alignment of each crystal with the collimated beam with a probable accuracy of not better than $\pm 2^{\circ}$. While it was known that this did not represent the most satisfactory condition, it was felt that the search for the critical angle would result in aligning at least the first crystal with the beam so

that reflection would occur and that the planes of the crystals aligned behind it would at least accept a small percentage of the scattered photons at the critical angle and thereby increase the percentage of total photons reflected. The data which were obtained with the crystals aligned for reflection are tabulated in Table 7 and plotted with a solid line in Figure 11. The platform and crystals were then rotated clockwise through an arbitrarily chosen angle of 10° to insure that the collimated beam was no longer incident at the proper angle for reflection to occur and a survey was made as before of the gamma radiation which was reflected and scattered. These data have been tabulated in Table 8 and plotted in Figure 11.

Comparing the reflected data to the scattered data in Figure 11, one can see that a similar pattern exists as did with the previous specimen. The number of photons which were detected on the centerline showed a decrease of approximately 7.2 per cent and a general increase of the order of 10 per cent over a broad sector from 16° to 60°. This pattern was interpreted as a rather definite indication that photons had been deflected through large angles by repeated reflections from the crystal planes. The increased counting rate in the negative sector is believed to have been caused by the orientation of some of the crystal planes such that they curved initially into the negative quadrant as explained above. In

addition, attention should be called again to the fact that the scintillation detector could not discriminate sharply against photons only 5° off the axis of the probe and thus a sizeable portion of the radiation detected at -5° included photons on the axis of the collimated beam.

The results of this experimentation indicate that large scale deflection of gamma rays through repeated reflections from a curved surface can be obtained utilizing crystal planes as curved elements. It is strongly recommended that further study be continued toward the attainment of an arrangement of curved elements which can secure a large scale deflection of gamma rays with a higher order of efficiency than was evident with the specimens chosen for this study.

It was felt that the results obtained could have been improved considerably with the following modifications in the procedure and equipment:

1. Several types of single crystals should have been obtained and the values of the critical angles required for reflection determined by measurement rather than by hypothesis. This would probably be the most fruitful field of research toward the verification and advancement of the theory of gamma ray reflection.
2. If crystals were chosen for further study of large scale photon deflection, the acquisition of a freshly

grown, unstressed, single crystal would be sought with slightly greater dimensions than were used herein and with the most dense planes aligned parallel to the longest dimension. It was felt that the results obtained were inhibited by the fact that the zinc crystals used had been stressed prior to use as reflecting surfaces. In addition, the basal planes were oriented so that the greatest dimension was of the order of one-half inch so that they had to be bent rather sharply to obtain a large deflection. This detracted from the advantage of using a single crystal in that a greater number of imperfections were necessarily introduced.

3. The experimental arrangement should be modified to allow for a sharper discrimination against radiation off the axis of the detector than was obtained herein. This would be particularly helpful in the analysis of the data obtained at positions only a few degrees off the axis of the collimated beam.
4. A positive means should be devised for the alignment of the curved elements with the collimated beam. While the method used was found to be satisfactory, much would be gained if a predetermined critical angle could be set and checked with a high degree of accuracy.

The use of an electrodeposited curved element as a reflecting surface bears a good deal of further study. Evidence has been given in the literature that twins are formed during the electrodeposition of copper and that these twins are roughly parallel to the surface upon which the copper is deposited. A study along this line would probably have to begin with a detailed study of the mechanism of electrodeposition with a view toward establishing the conditions required for such a structure to be formed.

The importance of the theory of gamma ray reflection cannot be over-emphasized since it represents a possible means for the design and the construction of a lighter-weight shield than is presently available. The development of a light-weight gamma ray shield based on the absorption of gamma rays does not show much promise since it has been shown, Glasstone (10), that the weight of a gamma ray shield is essentially independent of the material selected if one is to rely solely on absorption. At the present time, the aircraft industry is seriously hampered in its efforts to launch a nuclear powered aircraft largely due to the weight of the shielding which is required. With the hope that the end results will be evident in the construction of a light-weight but space-saving shield design, the further study of gamma ray reflection is strongly recommended.

VIII. CONCLUSIONS

The following conclusions were drawn from a consideration of the theory involved and the experimental results:

1. Despite the fact that zinc crystals do not represent the most efficient material for reflection of gamma rays, large scale deflections through repeated reflections from curved crystal planes are in evidence.
2. Improved results can be obtained with various refinements in the experimental arrangement and more selective choice of materials.
3. The use of an electrodeposited, curved element for the reflection of gamma rays is worthy of further study.
4. A study of the use of a single curved element as a reflecting surface should yield very significant results but will probably not be useful in the construction of a gamma shield utilizing reflecting elements.

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